Guidance Material on collection of Ionospheric Scintillation data at strategic locations in the Low-latitude Region

(Ver. 1)

1. Background

The second meeting of Ionospheric Studies Task Force (ISTF/2) noted the limited scintillation monitoring facilities established in the region, and decided to develop a guidance material on collection of scintillation data at strategic locations (Action Item 1). This document has been developed to address the AI-1 of ISTF/2.

There are two types of ionospheric scintillations in GPS measurements, amplitude and phase scintillations. Amplitude scintillation refers to rapid fluctuation in signal intensity (or carrier-to-noise ratio, C/N0) measured by a receiver, while phase scintillation refers to rapid fluctuation in the carrier-phase measurements. Levels of amplitude and phase scintillations are commonly represented by the standard deviations of amplitude and phase, respectively S4 and σ_φ, in a certain time period (typically 1 min). The ways of estimating the S4 and σ_φ indices are given in Appendices A.1 and A.2.

For the amplitude scintillation, rapid sampling of C/N0 is necessary, while rapid carrier-phase measurements are required for the phase scintillation. Furthermore, GPS receivers for phase scintillation measurements need to be equipped with a highly stable clock (oscillator) such as OCXO (oven-controlled crystal oscillator) to distinguish the phase fluctuations due to ionospheric scintillation and clock (oscillator) noise.

Both types of ionospheric scintillations are caused by plasma irregularities in the ionosphere. In the low-latitude regions where the background electron density is high and plasma drift velocity is relatively slow, the amplitude scintillation is dominant. In this guidance, therefore, the amplitude scintillation is focused on.

2. Receiver performance

2.1 Receiving frequency

Since only the GPS L1 (1.57542 GHz) is currently used, GPS L1 single-frequency receivers satisfying other performance requirements in this section are acceptable. In addition to GPS, however, receivers should be capable of GLONASS and SBAS GEO satellites for wide coverage of the sky.

For the use of the L5 frequency in the future, receivers capable of tracking L1 and L5 signals would be a good choice.

If a receiver could track L2 frequency, it could be used to measure ionospheric delays (or ionospheric total electron contents (TECs)).

2.2 Receiver clock

Since the amplitude scintillation is of interest, a highly stable clock is not necessary, but a standard clock such as TCXO (temperature compensated crystal oscillator) is enough.

2.3 Sampling rate

The amplitude scintillation is caused by the Fresnel diffraction due to the ionospheric irregularities. The typical scale size causing the Fresnel diffraction (D_F) is described as

$$D_F = \sqrt{2\lambda h} \tag{1}$$

where λ is the wavelength of the radio wave (0.19 m for the GPS L1 frequency) and h the height of the irregularities (typically 300-400 km). Thus, the typical scale size is 300-400 m. The amplitude will fluctuate at the Fresnel frequency

$$f_F = V / D_F \tag{2}$$

where V is the drift velocity of the irregularities. Since the drift velocity of plasma irregularities (V) is typically 100-200 m/s, the amplitude will fluctuate at 0.25-0.67 Hz.

According to the sampling theory, the sampling rate of the amplitude should be at least twice as fast as the Fresnel frequency, 0.5-1.33 Hz. Considering that the spectrum of amplitude fluctuation contains higher frequency components, the sampling rate should be much higher than the Fresnel frequency. It is common to sample the amplitude at 20 Hz or more. It should also be noted that the default sampling rate of the amplitude by the widely used GSV4004B receiver is 50 Hz.

The raw amplitude measurements at high sampling rates can be recorded. However, it would take a lot of file size. Therefore, the raw amplitude measurements could be discarded after calculating and recording scintillation intensity, although the raw amplitude measurements data would still be useful for future re-analysis and irregularity drift measurements with closely spaced scintillation receivers.

If the ionospheric delay is desired to be derived, both the pseudo-range and carrier-phase need to be sampled. However, the sampling rates of them do not have to be the same as the amplitudes, but can be much slower than that of the amplitude. The typical sampling rate for the ionospheric delay measurements is 1 sec. (For GBAS, the minimum sampling rate of a ground subsystem is 2 Hz, though)

TEC measurements can also be used to derive another index of ionospheric irregularities: the rate of TEC Index (ROTI). ROTI is defined as the standard deviation of rate of TEC in a certain time period, typically 5 min [2]. ROTI is another indicator of ionospheric irregularities that can be derived from standard low sampling rate dual-frequency receiver measurements. The way of estimating ROTI is given in Appendix A.3.

2.4 Multi-path effect avoidance

The measured amplitude often fluctuates at low elevation angles due to multi-path effects and result in artificial enhancements in the scintillation level. There are two ways to eliminate the multi-path effects. One is simply to set a higher elevation mask such as 30º. However, it would have a drawback of loosing data at low elevation angles where the path length in the ionosphere is long and more scintillation is expected.

Alternatively, the standard deviation of the code-carrier divergence (sigma-CCD) can be utilized. The code-carrier divergence is the difference between the rates of change in pseudo-range and carrier-phase measurements. When there is no multi-path and ionospheric effects, the rates of change in pseudo-range and carrier-phase changes will be the same, except for ambient and receiver internal noises.

The multi-path signal generally accompanies much larger sigma-CCD than ionospheric scintillation signal, which can be used to distinguish between scintillation enhancements by multi-path and ionospheric irregularities [1]. If a sigma-CCD value calculated for the same period as the S4 index exceeds a certain limit, the signal is likely to be affected by multi-path effects. To do this, the pseudo-range and carrier-phase need to be sampled at a certain rate, such as 1 Hz. Sigma-CCD can be calculated afterwards if the pseudo-range and carrier-phase are recorded, while some receivers such as GSV4004B can calculate sigma-CCD internally and record it. The way of deriving the sigma-CCD is given in Appendix A.4.

2.5 Other useful measurements

The satellite azimuth and elevation angles are not essential, but will make post-analysis easier. The sampling rates of the azimuth and elevation angles can be as low as those of the pseudo-range and carrier-phase.

2.6 Summary

The receiver should be able to track at least GPS L1 frequency signals. Tracking capability of GLONASS and SBAS GEO satellites are very useful.

The receiver do not have to be equipped with a highly stable clock (oscillator) as long as it is used for the amplitude scintillation measurements, which is the case in the low latitude regions.

The most important value to be recorded for the low latitude ionospheric scintillation is the amplitudes (C/N0) of the signal for each satellite. The sampling rate should be much higher than the Fresnel frequency and typically 20 Hz or more. Once the scintillation intensity is calculated and recorded, the raw amplitude measurements data can be discarded, unless future re-analysis or irregularity drift velocity measurements are not planned.

The pseudo-range and carrier-phase can be recorded at relatively low rates than the amplitude, such as 1 Hz. They are not mandatory, but useful to distinguish between ionospheric scintillation and multi-path signals.

The satellite azimuth and elevation angles are not essential, but will make post-analysis easier, if recorded together.

3. Antenna

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3.1 Antenna frequency

Antenna should be able to track signals corresponding to the signals which are desired to be tracked by the receiver.

As described in 2.1, an antenna capable of tracking L1 and L5 signals is a good choice.

3.2 Antenna type

To avoid the multi-path effect as much as possible, a choke-ring antenna or others with equivalent multi-path-resistant performance are preferable. Simple antennas could be used, but with a drawback of lower data availability especially at low elevation angles.

3.3 Antenna environment

Antennas should be located at places with the open sky without obstacles that may shadow satellites down to the elevation angle as low as possible.

The antenna site should be free from obstacles as wide as possible to avoid multi-path effects. Practically, it is very difficult to find ideal antenna locations. Therefore, the sigma-CCD filtering is very useful to enhance data availability under the multi-path conditions.

For example, installation of receiver in localizer building is recommended owing to its strategic location which is usually free from multipath. However, seaside runways are at disadvantage. We have observed more multipath effects in scintillation at sites surrounded by ocean.

3.4 Antenna separation

When more than one scintillation receivers are available, one can consider operating them with spaced antenna groups. There are some advantages of spaced antenna measurements.

With a few 100 m to a few kilometers antenna separation and the high frequency C/N0 data recording, drift velocity of ionospheric irregularities causing scintillation can be derived from the time lag between the two C/N0 variation patterns. It could potentially used to predict propagation of the ionospheric irregularities.

Spaced antenna measurements with separation of several tens to a hundred kilometers, which is comparable to the typical scale size of plasma bubbles contribute to increase the number of points probed by the GNSS signals to achieve spatially denser observations.

Multiple receiver measurements at multiple locations that share common sky () would be useful for redundant measurements against receiver failure. The radius of the area of the ionosphere that can be probed at an altitude of 350 km is about 560 and 1600 km for elevation mask angles of 30 and 5º, respectively.

4. Cables

A cable between an antenna and a receiver should be selected so that the signal level at the front-end of the receiver is in the range suitable for each receiver.

The expected signal level at the front-end of the receiver (P_{in}) is given by

$$P_{in} = P_{nom} + G_{ant} + G_{pa} + L_{cable} + G_{ila} \qquad (3)$$

where P_{nom} is the nominal signal level at the antenna, G_{ant} the antenna gain, G_{pa} the gain of the preamplifier, L_{cable} the cable loss, and G_{ila} the gain of an in-line amplifier. The nominal signal level of GPS on the ground is between -153 and -160 dBm for L1 C/A signal [3]. G_{ant} and G_{pa} depends on the antenna model. L_{cable} is determined by the type, thickness of the cable and proportional to the length.

Cable length should be determined so that P_{in} is in the range of signal level suitable for the receiver. When the cable has to be too long to keep P_{in} in the suitable range, an in-line amplifier can be inserted between the antenna and the receiver. However, the gain should not be too high not to exceed the upper limit of the input signal level.

5. References

[1] Van Dierendonck, A. J., and Q. Hua, Measuring ionospheric scintillation effects from GPS signals, proceedings of ION 57th Annual Meeting, 391-396, 2001;

[2] Pi, X., A. J. Mannucci, U. J. Lindqwister, and C. M. Ho, Monitoring of global ionospheric irregularities using the worldwide GPS network, Geophysical Research Letters, 24, 2283-2286,1997;

[3] ICD-GPS-200 IRN-200C-004, Navstar GPS Space Segment / Navigation User Interfaces. April 2000.

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Appendix A. Parameter estimation

A.1 Amplitude scintillation index (S4 index)

The amplitude scintillation index (S4 index) is defined as a normalized standard deviation of C/N0 as given by:

$$S4 = \sqrt{\frac{\langle s_i^2 \rangle - \langle s_i \rangle^2}{\langle s_i \rangle^2}} \tag{4}$$

where < > denotes average , and s_i is the C/N0 in linear scale (not in dBHz) of the i-th satellite. The linear-scale C/N0 (s_i) is related to the C/N0 in dBHz (c_i) as:

$$s_i = 10^{(0.1 \times C_i)} \tag{5}$$

The period of taking average depends on the time scale of interest. It is common to calculate S4 every 1 min (i.e., the averaging period of 1 min).

A.2 Phase scintillation index (σ_φ)

The phase scintillation index (σ_φ) is basically a standard deviation of carrier-phase measurements. However, the carrier-phase measurements have a trend associated with the change of the geometric range. Therefore, the carrier-phase measurements have to be detrended first.

Defining φ’ as the detrended carrier-phase measurements, σ_φ can be defined as:

$$\sigma_\varphi = \sqrt{\langle \varphi'^2 \rangle - \langle \varphi' \rangle^2} \tag{6}$$

A.3 Rate of TEC index (ROTI)

ROTI is defined for each satellite as the standard deviation of rate of TEC (ROT) as given by:

$$ROTI_i = \langle ROT_i^2 \rangle - \langle ROT_i \rangle^2 \tag{7}$$

where ROT_i is the rate of TEC of the i-th satellite in the unit of TEC/min as given by:

$$ROT_i(t) = \left(TEC_i(t) - TEC_i(t-\tau)\right)/\tau \tag{8}$$

where τ is the sampling interval.

A.4 Sigma-CCD

Sigma-CCD is defined for each satellite as the standard deviation of code-carrier divergence as given by:

$$SigmaCCD_i = \left\langle d_i^2 \right\rangle - \left\langle d_i \right\rangle^2 \qquad (9)$$

where d_i is the code-carrier divergence of the i-th satellite as given by:

$$d_i = \left(\rho_i(t+\tau) - \rho_i(t)\right) - \left(\varphi_i(t+\tau) - \varphi_i(t)\right) \qquad (10)$$

where $\rho_i(t)$ and $\varphi_i(t)$ are respectively the pseudo-range and carrier-phase measurements of the i-th satellite at a time t, and τ is the sampling interval of the pseudo-range and carrier-phase.

The period of taking average should be the same as S4 index, and typically 1 min. The sampling interval of the pseudo-range and carrier-phase is typically 1 sec.

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